Where is Waldo at time *t* ?

Using spatio-temporal models for mobile robot search

Tomáš Krajník, Miroslav Kulich, Lenka Mudrová, Rares Andrei Ambrus, Tom Duckett

tkrajnik@lincoln.ac.uk, kulich@ciirck.cvut.cz , mudrole@bham.ac.uk, aambrus@kth.se, tduckett@lincoln.ac.uk

University of Lincoln, UK Czech Technical University, CZ University of Birmingham, UK Royal Institute of Technology, Sweden

L-CAS Lincoln Centre for Autonomous Systems

Introduction

- A novel approach to mobile robot search in changing environments.
- The goal is to plan a path, which minimizes the search time
- The searched object position is not static, but its occurrence in particular locations is a quasi-periodic function of time
- Compared to methods that consider the locations of objects as static, our approach reduces the search times by 35% to 65%

Object search

- Formally defined as a variant of the Graph Searching problem
- The objective is to find a walk $\boldsymbol{\omega}$ in a graph, which visits all vertices and minimizes the expected time to find the object:

$$\boldsymbol{\omega} = \arg\min_{w\in\Omega} \mathbb{E}(T|w) = \sum_{i=0}^{|w|} \tau^w(i) p(w_i), \text{ where}$$

$$\tau^w(i) = \sum_{\iota=0}^{t} d(w_\iota v_{w_{\iota+1}})$$

- The minimal expected time is then

$$T_{exp} = \mathbb{E}(T|\boldsymbol{\omega}) = \sum_{i=0}^{|\omega|} \tau^{\boldsymbol{\omega}}(i) p(\omega_i)$$

- The proposed search algorithm is a variant of branch-and-bound based on a recursive version of depth first search
- Several improvements were made to achieve an effective branching and low computational time:
  - short distances are process first during vertex expansion
  - Johnson's all-pairs shortest path algorithm employed in the preprocessing phase
  - Estimated cost (lower bound of all walks with a prefix w) is determined as

$$T^{exp}(w) = \mathbb{E}(T|w) + \sum_{i=0}^{K} p_i D_i, \text{ where}$$

$$D_i = D(w) + \sum_{\iota=0}^{i} d_\iota,$$

- Exact search for Experiment 2 with 11 vertices took 1ms, a problem with 20 vertices took 6 s, and for a graph with 25 vertices 60 s on a standard computer

Frequency Map Enhancement

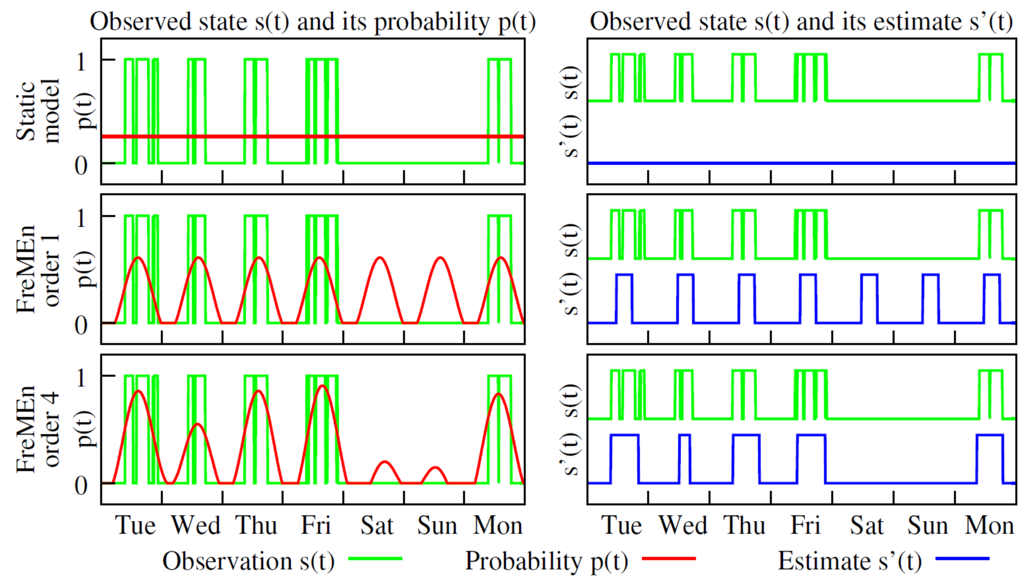
- Allows to identify reoccurring patterns from long-term observations and use them to predict the future environment states
- Based on a (non-uniform) Fourier transform techniques
- The uncertainty of a state is modelled as a probability in time:

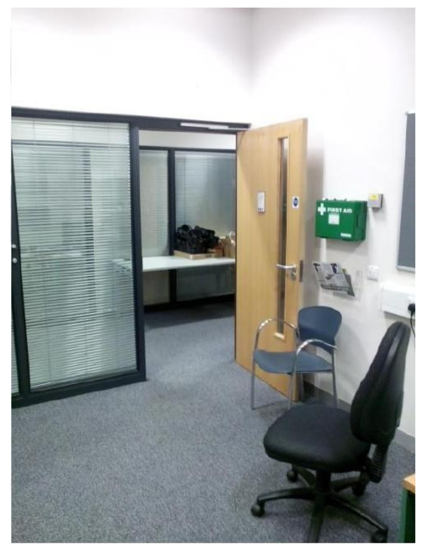
$$p(t) = p_0 + \sum_{j=1}^{n} p_j cos(\omega_j t + \varphi_j) \qquad (1)$$

- The parameters of Equation (1) can be obtained from observations of the state s at times t_k by a non-uniform Fourier transform:

$$S(\omega) = \sum_k (s(t_k) - p_0) e^{-jt_k\omega} \qquad (2)$$

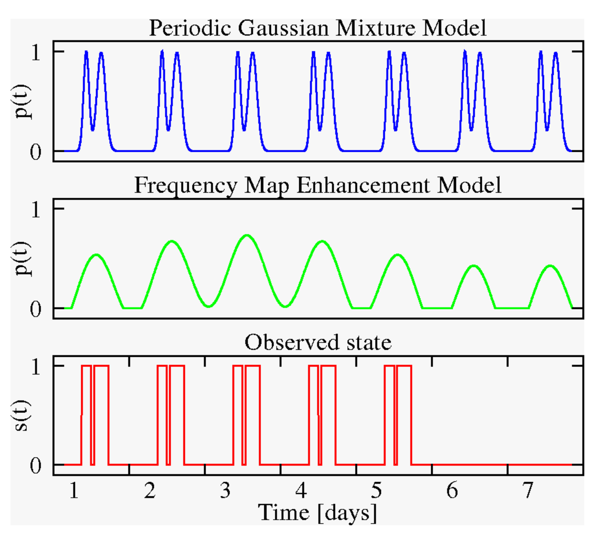
- **Example:** week-long observation of an office door





Periodic Gaussian Mixtures

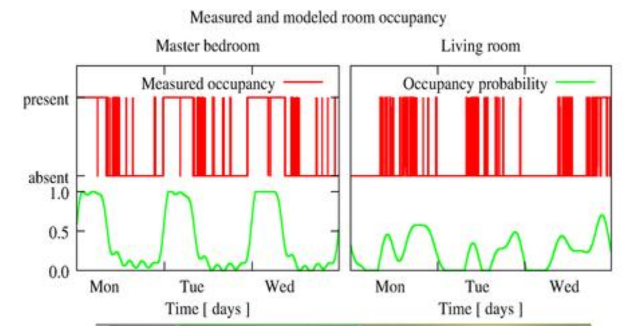
- The FreMEn cannot properly model short-duration events
- Alternative temporal model based on Gaussian mixtures allows to model short events, but can consider only one periodicity

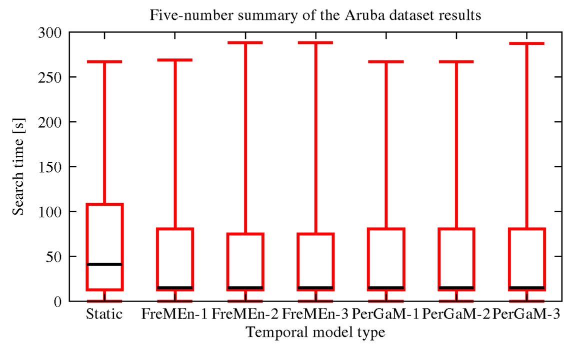


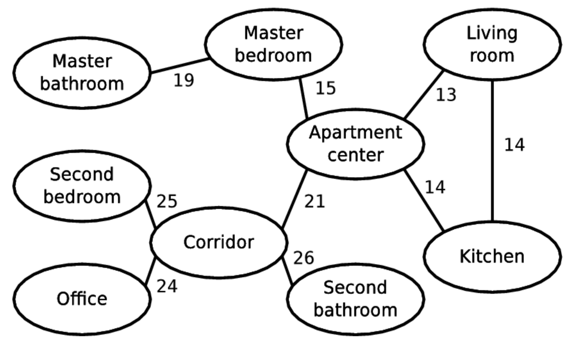
The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement No. 600623, `STRANDS' and from the Technology Agency of the Czech Republic under grant agreement No. TE01020197, `Centre for applied Cybernetics'.

Experiment 1: Apartment

- Constructed a topological map using a 4 week long data from a monitored real apartment occupied by a house-bound person [2]
- Reconstructed the apartment in a robotic simulator and established the times needed to travel between the individual areas
- Used additional 12 week-long data from [2] to determine the time needed to find the person

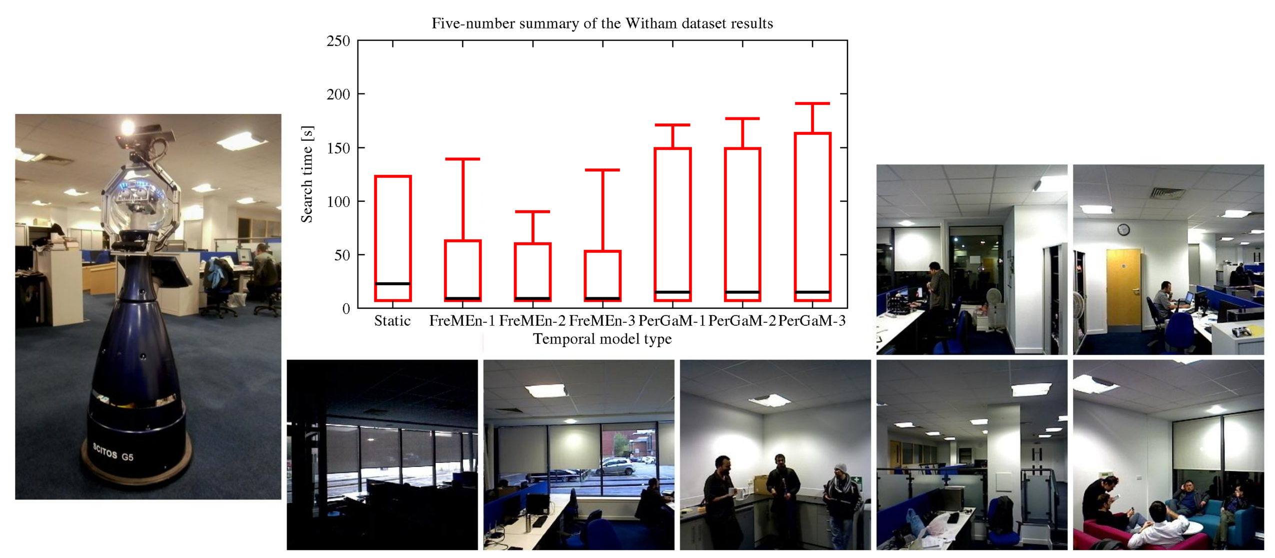






Experiment 2: Office

- A SCITOS-G5 mobile robot monitored 8 areas of an open-space office for one week to build the person presence models
- Two additional days used to determine the search times



References

[1] T. Krajník *et al.*: *Spectral analysis for long-term mapping.* In ICRA`14.
[2] M. Kulich *et al.*: *Single robot search for a stationary object in an unknown environment.* In ICRA`14.
[3] D.J. Cook: *Learning setting-generalized activity models for smart spaces, IEEE Intelligent Systems.* (2010)